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by Robert E. English and Ruth N. Weltmann
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Symposium on Alkali Metal Coolants - Corrosion and System Operating Experience sponsored by the International Atomic Energy Agency Vienna, Austria, November 28-December 2, 1966.

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ABSTRACT

As a preliminary to development of a reactor-powered alkali metal-vapor turbogenerator power system for use in space, components of such a system have been studied and operated in various alkali metal loops. The observed performance of the components and the experience in operation of the loops are both described. Although the work encompasses both sodium and potassium, the work with potassium is emphasized.

Heat transfer to boiling potassium was investigated in a 300 kW loop of L-605 for temperatures as high as 1750° F and in a 150 kW loop of Cb-1Zr for temperatures as high as 2100° F. In addition, heat transfer to boiling sodium was investigated in a 500 kW bimetallic loop of Cb-1Zr and 316 stainless steel; the boiling temperature reached 2000° F. Condensation of potassium at temperatures of 1200° - 1500° F was investigated in two loops of 50 and 150 kW capacity. Wet potassium vapor at 1500° F was produced by a 3 MW gas-fired boiler and supplied to a 2-stage turbine; although the entire loop was built of 316 stainless steel, the turbine rotor blades were of TZC, TZM, and Udimet 700 for purposes of comparison of erosion resistance. Condition of the turbine at the end of an endurance run of 5000 hours is described. Alkali metals at 1100° and 1980° F were pumped for several thousand hours by, respectively, a motor-driven centrifugal pump designed for flight and an electromagnetic induction pump; the pump designs are described. Both electrical and magnetic materials for long-time use at 1100° F have been investigated; results of these tests are presented. The methods used for measurement of fluctuating pressure in these alkali metal systems are also described.

Author

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## INTRODUCTION

The investigation of alkali-metal power systems by the National Aeronautics and Space Administration has as its objective long-lived space power systems having electric power outputs of the order of 100 kW to 10 MW. This power might be either for electric propulsion or for powering equipment within the spacecraft. For these high powers, both the area and the mass of the waste-heat radiator are important factors in selection of a Rankine-cycle system operating at high temperature and using an alkali-metal vapor as the working fluid. The considerable experience here on Earth with turbogenerating Rankine-cycle powerplants and the long lives of these powerplants indicate that a similar turbogenerating powerplant might possess a comparable long life in space. Nuclear reactors might provide the required thermal energy with only small additions of mass and volume to the powerplant.

The type of system being investigated is shown in figure 1 and contains four separate fluid loops. The temperatures shown illustrate the levels that might be used; these temperatures, although high, are within the capabilities of the alloy T-111 (Ta-8W-2Hf). The liquid coolant pumped through the reactor flows through the boiler, where its temperature drops $100^\circ$ to $200^\circ$ F. One of the main reasons for use of a separate loop for the reactor is to diminish the problems of shielding against nuclear radiation. If some of the reactor fuel elements develop small cracks, the reactor might well be capable of continued operation, but some of the fission products could then leak into the reactor coolant stream. With a separate reactor loop, only the reactor loop need be shielded in order to protect against such fission product leakage. If a separate reactor loop were not used, these fission products would contaminate the entire power loop, and thereby shielding, inspection, and maintenance of the power system would be complicated.

For the power loop, potassium is the working fluid. In the counterflow boiler, the maximum temperature at which the potassium may be boiled is approximately the same as the temperature of the reactor coolant as it leaves the boiler. For this reason, some superheating of the resulting potassium vapor is possible, of the order of $50^{\circ}$ to $150^{\circ}$ F. The turbine outlet temperature of $1350^{\circ}$ F produces minimum radiator area per unit power for the specified boiling conditions.

The potassium vapor at the turbine discharge is condensed by transfer of heat to a counterflowing liquid, this liquid then being cooled by means of thermal radiation to space. The condensing and radiating functions are separated for two reasons. First, system weight is reduced if liquid rather than vapor of low density passes through the radiator tubes because the smaller liquid-filled radiator tubes require less armor against meteoroid penetration than do the larger vapor-filled tubes. And second, the design of the power loop is then almost independent of the manner in which the power system integrates with the spacecraft and mission. Radiator geometry can be adapted to each spacecraft and mission with only minor alterations in pumping power.

Such a power system as this has a considerable number of components and a substantial diversity of problems. To this time, various constituent problems of many of these components and the physical properties of potassium vapor and liquid have been investigated both within the NASA laboratories and under contract [1] to [5]. A number of these investigations are described below. For brevity, the discussion is limited to components of the power loop.

## HEAT TRANSFER

For design of potassium boilers and condensers, the heat transfer characteristics of the liquid, two-phase, and vapor potassium working fluid have to be known. Many facilities have been developed and operated to test boilers and condensers of different design, to obtain sufficient heat transfer information, and to develop these two components for a space power system [6,7]. Two different types of boiler test facilities were operated to obtain heat transfer information for all conditions of boiling of potassium and for different boiler geometries [8 to 11]. Different boiler geometries are used to improve the heat transfer and obtain once-through boiling; that is, subcooled liquid potassium enters one end of heated tubes and dry, superheated vapor leaves the other end.

Several types of test apparatus were used for investigation of boiling potassium, one rig being shown schematically in figure 2. This apparatus, built of L-605 (Co-20Cr-15W-10Ni, nominal alloy composition in weight percent), was operated for investigation of boiling potassium temperatures up to $1750^{\circ}$ F. Heat was added to the boiling potassium by a flowing stream of liquid sodium that itself was heated by a 300-kW gas-fired heater. An air-cooled condenser cooled the potassium, and the potassium and sodium streams were each circulated by an electromagnetic pump. In the potassium boiler, the sodium and potassium flows through concentric tubes, the potassium being in the inner tube. In some tests the sodium and potassium flows were countercurrent with respect to one another, and in other tests cocurrent. Thermocouples spaced axially along the outer sodium tube indicated the axial distribution of heat transferred to the potassium. In some of the potassium boilers, a vortex-generating insert extended the full length of the potassium tube in order to provide high centripetal acceleration for phase separation; thermocouples located in this central body indicated the axial distribution of both the pressure and temperature of the boiling potassium. Potassium pressures at boiler inlet and outlet were measured by means of slack diaphragm transducers. This test apparatus was operated for over 4000 hours.

Typical data of local heat flux, quality and heat transfer coefficient along the boiler length are presented for one of the test boilers in figure 3. The local heat flux at the entrance to the boiler is very large (over 200,000 Btu/(hr)-(ft$^2$)) because the temperature difference between the potassium and the sodium heating fluid is great. Heating the potassium decreases the heat flux because of decreasing temperature difference. The heat flux in the nucleate boiling region increases primarily because of the increased heat transfer coefficient for this mode of heat transfer. At a vapor quality of about 75 percent, the heat flux and heat transfer coefficient begin to decrease, marking the onset of critical heat flux and the beginning of the transition-boiling region. In the superheat region, the heat flux and heat transfer coefficient have fallen to values typical of the heat transfer to gases. In figure 4, the average heat transfer coefficients with and without an insert are compared. The insert was a helix wound on a cylindrical center body that extended radially from the tube wall to the wall of the center body; the pitch of the helix was twice the tube inside diameter. High heat transfer coefficients were obtained at intermediate qualities either with or without the insert. The low heat transfer coefficients at low quality result from low fluid velocities and are readily increased by reduction in flow area. At high vapor quality, the decline in heat transfer coefficient in the transition region is markedly delayed by the presence of the helical insert. With the insert, 200$^\circ$ F of superheat was obtained, but without the insert 100 percent quality was not achieved.

Boiling of potassium at higher temperatures was investigated in the apparatus shown schematically in figure 5. This apparatus was built entirely of Nb-1Zr and so was capable of boiling potassium at temperatures as high as 2100$^\circ$ F. For protection against oxygen, the loop was contained in a vacuum chamber at $10^{-6}$ to $10^{-7}$ torr. The potassium stream was heated electrically in three successive heaters of a maximum capacity of 150 kW. The preheater and the preboiler heat liquid and low-quality potassium, respectively, in order to provide potassium of specified enthalpy at the inlet to the test boiler. The test boiler was heated by thermal radiation from its surrounding electric heater. The resulting vapor was condensed by thermal radiation and then pumped again to the boiler by an electromagnetic pump. The facility was operated in excess of 6000 hours.

The heat flux for boiling burnout, or critical heat flux, was measured with this apparatus in the following way: The preheater and the test boiler were operated at constant power, and high-speed recordings were made of the potassium flow and of various pressures and temperatures. Preboiler power was then increased. If under such conditions the wall temperature in the test boiler would suddenly rise (perhaps 200$^\circ$ F in 5 sec), the heat flux in the test boiler is the critical heat flux for boiling burnout.

In addition to these investigations of boiling potassium, boiling of sodium at temperatures as high as 2100° F was investigated in a 500-kW test rig, the boiler sections being built of Nb-1Zr and the others of stainless steel. This equipment has accumulated 900 hours of test time.

Condensing of potassium at temperatures from 1100° to 1500° F has been investigated in two rigs. One of these facilities supplied 50 kW of heat to boil potassium in a pot boiler. The potassium vapor was then condensed within a nickel tube by heat rejection to a countercurrent stream of sodium in a surrounding concentric tube. Except for the condensing tube itself, the test apparatus was built of 316 stainless steel and operated in air. Local heat transfer coefficients for potassium condensing at temperatures from 1100° to 1400° F were measured during 1200 hours of operating time [12 to 14].

A second rig for investigation of condensing-potassium heat transfer is shown in figure 6. Heated NaK was used to boil potassium which then flowed to either a radiatively- or a convectively-cooled condenser, the particular condenser being selected by settings of two shutoff valves. The radiatively-cooled condenser was enclosed within a vacuum chamber in order to avoid atmospheric convection, and the other condenser was cooled by circulation of cooled NaK. The 150-kW NaK heater and boiler were L-605 and the remainder of the system was 316-stainless steel. Condensing temperatures to 1500° F have been investigated during 900 hours of rig operation [15].

A convectively-cooled condenser is shown in figure 7. Potassium vapor condensed within seven parallel tubes, these tubes being cooled by a counterflow of NaK in a surrounding shell. The condenser had a bend in order to allow for thermal deformations of the tubes and shell. Thermocouples along the condenser shell indicated the temperature and energy content of the NaK and thus, indirectly, the energy content of the potassium. Pressure transducers measured potassium inlet pressure and overall pressure differential.

The general results of these heat transfer investigations of boiling and condensing potassium can be summarized as follows: High heat transfer coefficients in excess of $10^4$ Btu/(hr)(ft$^2$)(°F) are attainable both for condensing potassium and for boiling to intermediate qualities, such as 60 to 70 percent. The transition to the low heat transfer coefficients of gas heat transfer can be delayed until quality is near 100 percent if swirl-producing devices are employed. In general, condensing flows are stable, but boiling flows require some flow-stabilization device such as an orifice, especially in order to fix the zone of transition from all-liquid to boiling.

## TURBINE

For turbines having inlet temperatures of 2000° to 2200° F, creep strength of the rotor materials is a crucial question. The high centripetal accelerations imposed on the rotor's parts also make low density highly desirable. On the other hand, weldability and post-weld ductility are not as rigid requirements as for the piping and heat exchangers of the power system. For these reasons, alloyed molybdenum and niobium, which have about one-half the density of tantalum-base alloys, were investigated. The creep characteristics of the alloys TZC(Mo-1.25Ti-0.15Zr-0.12C), Cb-132M(Cb-20Ta-15W-5Mo-2Zr-0.13C), and TZM(Mo-0.5Ti-0.08Zr) are summarized in figure 8, in which the Larson-Miller parameter P relates temperature T ($^{\circ}$R) and time t (hr); these data were obtained by tests as long as 10 000 hours at temperatures as high as 2200$^{\circ}$ F. For the alloy TZC, less than 0.5 percent creep results from a stress of 20,000 lb/in.$^2$ at a temperature of 2000$^{\circ}$ F for a time of 10 000 hours. The TZM was also tested for compatibility with potassium vapor in a refluxing capsule at 2000$^{\circ}$ F for 5000 hours; there was no evidence of metallurgical attack.

A second crucial question about the turbine is the possibility of turbine blade erosion by liquid potassium droplets. For investigation of blade erosion, a two-stage turbine was designed, built, and tested in the apparatus shown in figure 9 [16 to 22]. The potassium boiler is a gas-fired multitube recirculating unit of three MW capacity. In order for the potassium entering the turbine to be near 100 percent quality, the vapor on leaving the boiler passes first through a wire-mesh demister and then through an inertia type of liquid separator. The turbine rotor is supported by oil-lubricated bearings, and a dynamic shaft seal prevents contact between the potassium and oil. A water-brake absorbs output power, and a steam turbine is used during startup to raise rotational speed to a value at which the dynamic potassium-oil seal functions. Because the entire loop was built of stainless steel, maximum metal temperature during operation is limited to 1600$^{\circ}$ F and turbine inlet temperature to about 1550$^{\circ}$ F.

A turbine performance test was completed in May 1965 and a 2000-hour endurance test in December 1965. An additional 3000-hour endurance test was completed in September 1966. Most of the rotor blades from the 2000-hour test were reinstalled in the rotor for the additional 3000-hour endurance test in order to accumulate 5000 hours on these blades.

Initially all of the turbine rotor blades were Udimet 700 (Ni-18Co-15Cr-5Mo-4.5Al-3.5Ti-0.3B). In the second stage, however, eight of the Udimet 700 blades were replaced by two pairs each of blades of TZM and TZC to obtain erosion data on actual candidate rotor blade materials. For the 5000 hours, the turbine was operated on potassium vapor under the following test conditions: inlet temperature, 1500$^{\circ}$ F; inlet vapor quality, 0.99; second-stage inlet quality, 0.97; rotor tip speed, 770 ft/sec; exit temperature, 1260$^{\circ}$ F; and exit quality, 0.93. After the test, the second-stage rotor blades were photographed (fig. 10) and weighed. No significant erosion is visible; some of the original machining marks can still be seen. The maximum change in blade weight was only $\pm$0.1 percent; these weight changes indicate that the erosion, if any, was negligible.

In order for turbine exit vapor quality to be at least as high as the 0.93 so far investigated, either liquid removal from the vapor stream or reheating is required. A single, direct expansion of the potassium vapor should produce about 0.88 vapor quality at the turbine exit. Turbine exit vapor quality can be increased by addition of a single reheating at an intermediate point in the expansion process or by a combination of liquid separation and reheating. If at one point in the expansion process vapor quality is increased to 100 percent, then minimum vapor quality in the turbines can be increased to 93 percent. Whether or not turbine exit vapor qualities of 0.85 to 0.90 will erode the turbine blades has not yet been investigated for potassium vapor. For investigation of this problem, the present two-stage turbine will be modified by addition of a third stage which will have an exit vapor quality of about 0.88. This three-stage turbine will then be subjected to a performance and endurance test for the same turbine inlet conditions used in endurance test of the two-stage turbine.

## PUMPS

For the type of power system being investigated (fig. 1), four pumps are required, one in each of the four loops. A motor-driven centrifugal pump is shown in figure 11; this unit, which is designed for flight, has pumped NaK at 1100° F for 3000 hours. The rotor of the motor is immersed in NaK, and the bearings are lubricated by NaK. Cooling of the motor's stator limits the hot-spot design temperature to 600° F [23]. The NaK temperature limit of 1100° F for this pump is adequate for all but the reactor loop of the potassium-vapor power system. However, the pump has to be redesigned for different flow rate and pressure head requirements.

As an alternative to a mechanical pump, an electromagnetic helical induction pump is being investigated for space application (fig. 12) [24 and 25]. In this type of pump, a 3-phase alternating current produces a rotating magnetic field that, in turn, produces eddy currents in the annulus of alkali metal. The resulting circumferential motion of the liquid metal creates axial motion as well because of hydrodynamic forces caused by the helical grooves in the flow annulus.

A pump of this type made of Nb-1Zr was used in a pumped loop for investigation of corrosion and in the boiling heat transfer rigs described previously. Although sodium at 1980° F was pumped for 5000 hours, the electrical and magnetic parts of the pump were cooled to 200° C in order that conventional electrical and magnetic materials might be used. These pumps are very inefficient (1 to 2 percent) but very reliable. A similar type of pump is now being investigated as a boiler-feed pump for the advanced potassium Rankine cycle (fig. 12) [26]; this more advanced pump is designed for its electrical and magnetic materials to operate at a temperature of 1000° F while pumping potassium at 1000° to 1400° F. This pump will have an efficiency of about 20 percent.

## ELECTRICAL MATERIALS

The pump just described, the turbine driven-alternator, and other electrical components of the power system all benefit from investigation of high-temperature electrical materials. Evaluation of various candidate materials resulted in selection of the following materials for further evaluation in small assembled electrical devices: magnetic material, Fe-27Co; electrical conductor, nickel-clad silver; conductor insulation, Anadur E glass serving plus refractory oxides; interlaminar and slot insulation, alumina; and end-turn potting compound, phosphate-bonded zirconium silicate [27,28]. Three types of electrical device were built for further evaluation of these materials and of their mutual compatibility; these devices were (1) a stator for a 3-phase 15 kVA alternator, (2) two solenoids, and (3) a transformer. These devices were placed in vacuum ovens, electrically energized, and maintained at a temperature of 1100° F for 5000 hours. With the single exception of the transformer, the performance of each device was as good at the end of the test as at the start. During the test, a short circuit occurred in the power supply. Another transformer is being built with some alteration in insulating materials, and this transformer will be subjected to endurance tests.

Materials for the rotor of the alternator have also been investigated, these materials being required to have both good magnetic properties and good strength at temperatures of the order of 1000° to 1100° F. For this reason, the creep strength of Nivco (Co-23Ni-1.1Zr-1.8Ti) was measured at temperatures of 1050° to 1150° F and times to 10 000 hours, the results being presented in figure 13. At 1050° F and 47 000 $lb/in.^2$, Nivco creeps 0.5 percent in 10,000 hours. At this temperature its useful magnetic flux is 10 000 gauss and its permeability 100.

## PRESSURE MEASUREMENT

Pressures of liquid, vapor, and two-phase alkali metals have to be measured. These pressures have generally been measured by using a slack diaphragm to isolate a low-temperature transducer from a high-temperature fluid. These devices have slow response and require careful temperature control. Two devices having faster response have been developed to measure pressures in alkali-metal systems.

The efflux pressure-measuring system shown in figure 14 balances the system pressure against a continuous stream of argon gas. Argon flows through a filter, a small metering orifice (0.005 in.), a valve, a vapor trap, and into the flowing alkali-metal vapor. The nearly continuous argon flow prevents alkali-metal vapor from entering the pressure-sensing tube. The argon flow is briefly interrupted, and the pressure in the sensing tube is then measured with a standard transducer. An emergency argon purge valve is connected to the sensing tube in order to flush out any metal vapors inadvertently entering the system [29]. The efflux system has a moderate frequency response but can be used only in systems that tolerate the presence of noncondensible argon in the alkali metal. The efflux measuring system has been used successfully in the NASA turbine test facility.

The other pressure measuring system (fig. 15) uses as the sensing element a W-25Re diaphragm shaped like a 2-convolution bellows. The displacement of the bellows is measured by a thermionic diode operating in the space-charge-limited mode. A second diode is used as a reference for the sensing diode, to linearize the output of the instrument, and to compensate for changes in emitter work function as a result of any emitter poisoning during the life of the instrument. The measuring diode consists of a heated planar circular emitter (cathode) in the center and a planar collector (anode) attached to the diaphragm. The second reference diode consists of a similar planar emitter and second collector a fixed distance from the emitting surface [30]. These pressure instruments have shown feasibility and are in the development stage. They can be used to measure pressures at temperatures up to 1800° F with a frequency response up to 100 cycles per second.

## CONCLUDING REMARKS

Although a substantial amount of knowledge has been accumulated on the various constituent problems of the potassium-vapor turbogenerator space power system, a very large amount of work yet remains before a system can be successfully demonstrated. On the bases of corrosion and strength, maximum temperatures of 2200° to perhaps 2400° F appear practical. Satisfactory data on thermodynamic properties of potassium are now available for design of such a powerplant. Knowledge of the heat transfer coefficients and pressure drop of boiling and condensing potassium is adequate to design single-tube boilers typical of a boiler segment for space power systems; multi-tube space boilers have yet to be investigated. The knowledge of boiling stability is advancing. For turbine-exit vapor qualities as low as 93 percent, turbine blade erosion has been acceptable; lower qualities must yet be investigated. In addition, a substantial amount of information is available for design of bearings, seals, pumps, and electrical components.

The program is now changing its general character from the technology and basic design phase to the demonstration of system components. Over the next several years, the major components of such a power system will be investigated.

## REFERENCES


### General

[1] Space Power Systems Advanced Technology Conference. Lewis Research Center, Cleveland, Ohio, August 23-24, 1966. NASA Special Publication SP-131, 1966.

### Properties

[2] Ewing, C. T., Stone, J. P., Spann, J. R., Steinkuller, E. W., Williams, D. D., Miller, R. R., High-temperature properties of potassium, U. S. Naval Res. Lab. Rep. NRL-6233 (1965).

[3] Lemmon, A. W., Jr., Deem, H. W., Eldridge, E. A., Hall, E. H., Matolich, J., Jr., Walling, J. F., Engineering properties of potassium, Battelle Memorial Inst. Rep. BATT-4673-Final (NASA CR-54017) (1963).

[4] Achener, P. Y., The determination of the latent heat of vaporization and vapor pressure of potassium from 1000° to 1900° F, USAEC Rep. AGN-8141 (1965).

[5] Tepper, F., Zelenak, J., Roehlich, F., May, V., Thermophysical and transport properties of liquid metals, MSA Res. Corp. (AFML-TR-65-99, AD-464138)(1965).

### Heat transfer

[6] Brooks, R. D., Ed., Alkali Metals boiling and condensing investigatigations, Vol. I - Experimental program, General Electric Co. (NASA CR-54050) (1964).

[7] Semmel, J. W., Jr., Young, W. R., Kearns, W. H., Alkali metals boiling and condensing investigations, Vol. II - Materials support, General Electric Co. Rep. GE63FPD66 (NASA CR-53406)(1963).

[8] Peterson J. R., High performance once-through boiling of potassium, USAEC Rep. CONF-651026 1 (1965) 357.

[9] Bond, J. A., Peterson, J. R., Tippets, F. E., Heat transfer and pressure drop measurements for high temperature boiling potassium in forced convection, USAEC Rep. ANL-7100 (1965)53.

[10] Peterson, J. R., High performance "once-through" boiling of potassium in single tubes. Topical Report, NASA Lewis Research Center Contract NAS 3-2528. To be published.

[11] Bond, J. A. and Converse, G. L., Vaporization of high-temperature potassium in forced convection. Topical Report, NASA Lewis Research Center Contract NAS 3-2528. To be published.

[12] Sawochka, S. G., Thermal and fluid dynamic performance of potassium condensing inside a tube, USAEC Rep. CONF-651026 1 (1965) 669.

[13] Sawochka, S. G., Measurements of forced convection condensing potassium heat transfer, USAEC Rep. ANL-7100 (1965)97.

[14] Sawochka, F. G., Thermal and fluid dynamic performance of potassium during condensation inside single tubes. Topical Report, NASA Lewis Research Center Contract NAS 3-2528. To be published.

[15] Gutierrez, O. A., Sekas, N. J., Acker, L. W., Fenn, D. B., Potassium condensing tests of horizontal multitude convective and radiative condensers operating at vapor temperatures of 1250° to 1500° F, USAEC Rep. CONF-651026 1 (1965) 694.

Turbine

[16] Rossbach, R. J., Space-vehicle Rankine-cycle power plant potassium-turbine development, ASME Paper 63-WA-326 (1963).

[17] Rossbach, R. J., Schnetzer, E., Nichols, H. E., Eckard, S. E., Performance test of a two-stage, 200 horsepower turbine in wet potassium vapor, USAEC Rep. CONF-651026 1 (1965) 521.

[18] Zimmerman, William, and Rossbach, Richard, Metallurgical and fluid dynamic results of a 2000-hour endurance test on a two-stage, 200 horse power turbine in wet potassium vapor. To be presented at Spring ASME Conference in Houston, Texas, March 5-9, 1967.

[19] Rossbach, Richard, and Wesling, Gordon, Two-stage potassium turbine - fluid dynamic design and performance. Topical Report, NASA Lewis Research Center Contract NAS 5-1143. To be published.

[20] Nichols, Herbert, Fink, Roy, Two-stage potassium turbine - mechanical design and development. Topical Report, NASA Lewis Research Center Contract NAS 5-1143. To be published.

[21] Eckard, Spurgeon, Two-stage potassium turbine test facility. Topical Report, NASA Lewis Research Center Contract NAS 5-1143. To be published.

[22] Semmel, J. W., Jr., Zimmerman, W., Hand, Robert, and Engleby, Dudley, Materials support, Vol. II. Topical Report, NASA Lewis Research Center Contract NAS 5-1143. To be published.

[23] Chalpin, E. S., Colker, C. P., Foss, C. L., Design and development of pumps for high temperature NaK service, USAEC Rep. CONF 651026 1 (1965) 186.

[24] Verkamp, J. P., Rhudy, R. G., Electromagnetic alkali metal pump research program, NASA Rep. CR-380 (1966).

[25] Rhudy, R. G., Verhamp, J. P., Electromagnetic pumps for space power systems, USAEC Rep. CONF-651026 1 (1965) 201.

[26] Electromagnetic pumps. Final Report, NASA Lewis Research Center Contract NAS 3-8500. To be published.

Electrical Materials

[27] Kueser, P. E., et al, Magnetic materials topical report, NASA Rep. CR-54091 (1964).

[28] Kueser, P. E., et al, Electrical conductor and electrical insulation topical report, NASA Rep. CR-54092 (1964).

Instruments

[29] Wesling, G. C., Rossbach, R. J., and Shaffernocker, W. M., Development of efflux measuring device for performance evaluation of potassium vapor turbine, USAEC Rep. ANL-7100 (1965) 127.

[30] Cassano, A. J., and Engdahl, R. E., Pressure transducer for liquid metal applications, USAEC Rep. ANL-7100 (1965) 165.

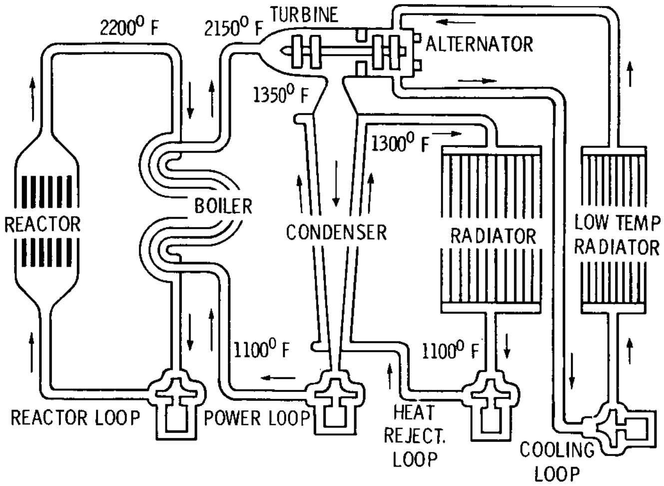


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Figure 1. - Potassium-Rankine system.

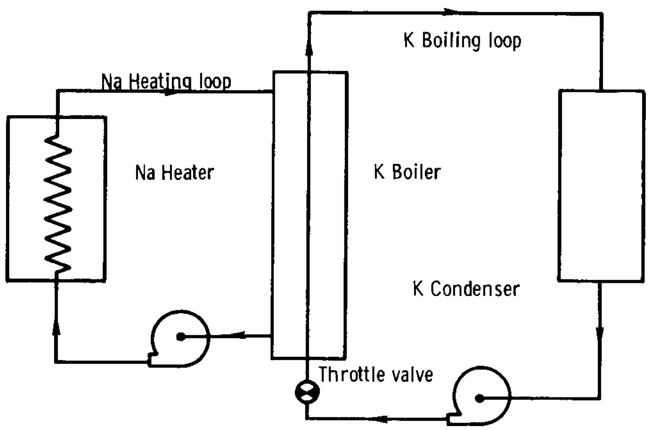


Figure 2. - Potassium 300 kW boiler rig.

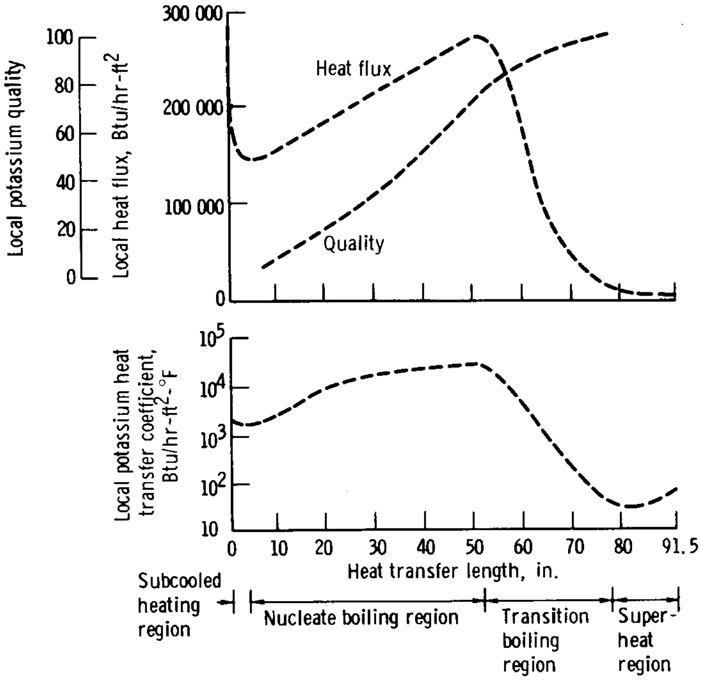


Figure 3. - Potassium boiler heat transfer characteristics.

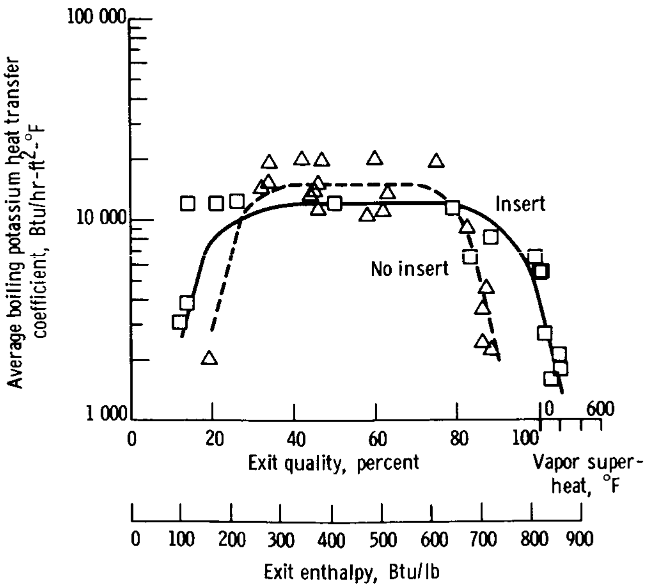


Figure 4. - Effect of insert on boiling potassium heat transfer. Insert: helical tape, pitch/diameter = 2.

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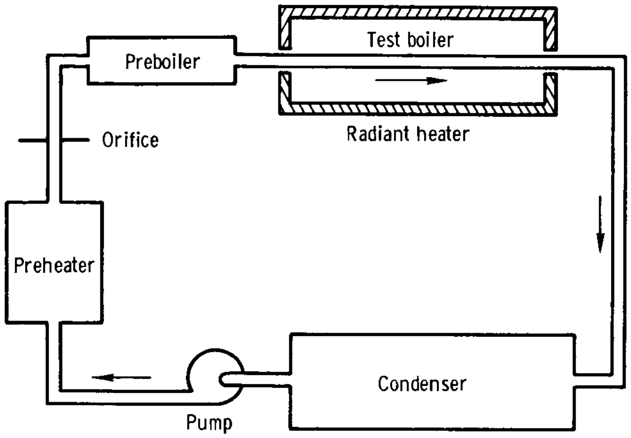



Figure 5. - 150 kW potassium boiler rig.

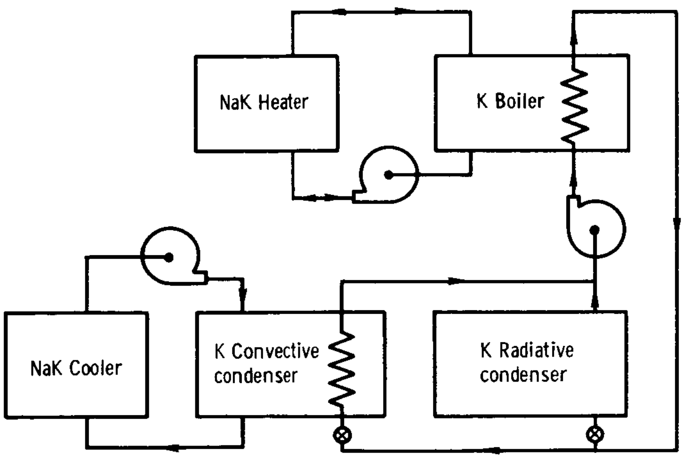



Figure 6. - Potassium condenser-radiator test rig.

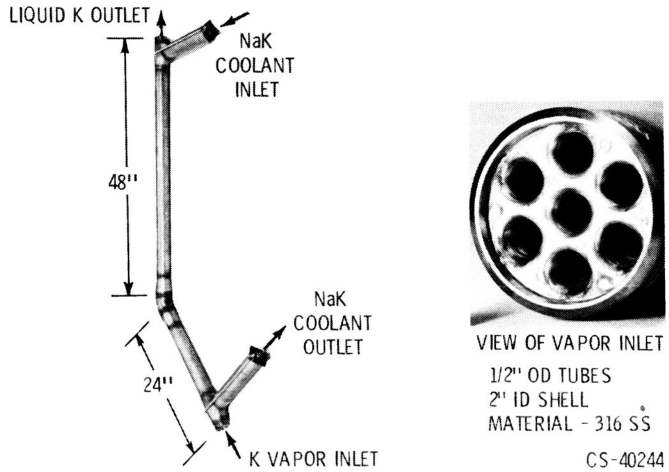



Figure 7. - Seven-tube K condenser.

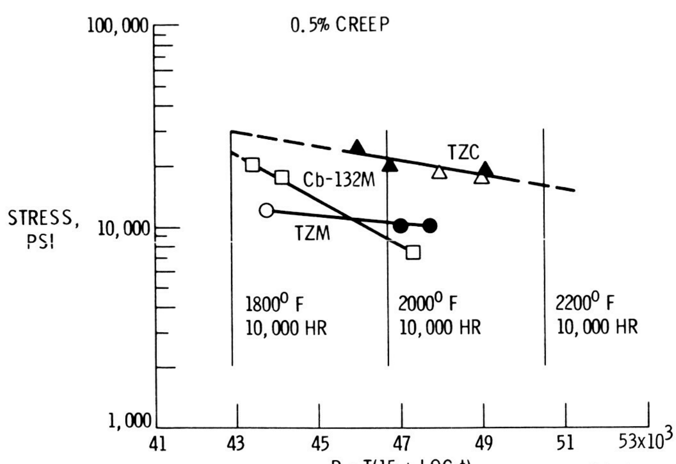



Figure 8. - Strength of turbine alloys

E-3593

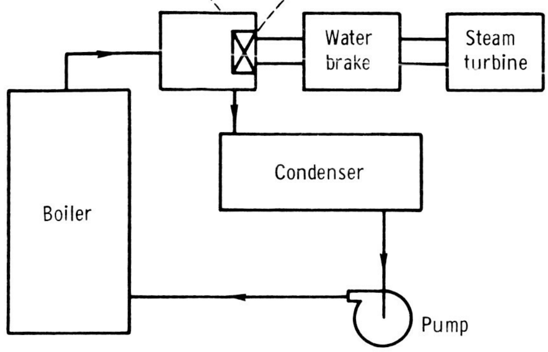
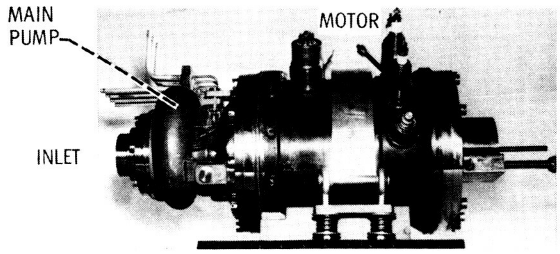



Figure 9. - Potassium turbine test loop.

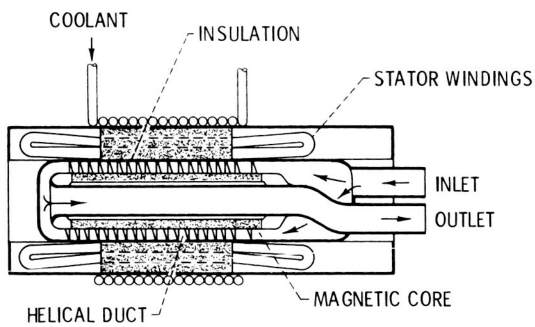
Figure 10. - Second-stage turbine rotor blades after 3000 and 5000 hours of operation with potassium vapor.




CS-40217

HEAD RISE: 35 PSI
FLOW: 35,300 LB/HR
INPUT POWER: 4.6 KW
OVERALL EFF: 35%
NaK LUBRICATED, TILTING PAD JOURNAL AND THRUST BEARINGS

Figure 11. - NaK pump-motor assembly.




HEAD RISE: 240 PSI
FLOW: 33 GPM
TEMP: 1000$^{0}$ F
EFFICIENCY: 0.20

CS-40500

Figure 12. - EM helical induction pump.

E-3593

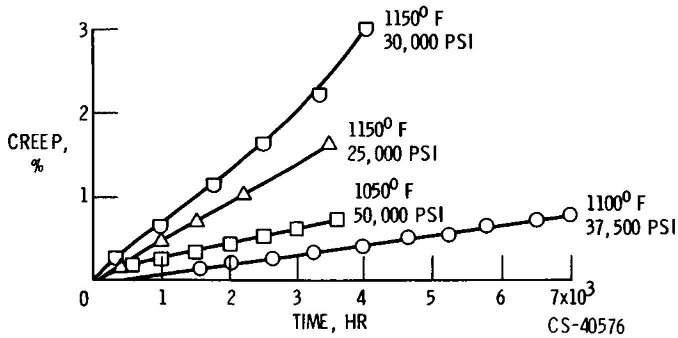



Figure 13. - Creep of Nivco. (Co-23Ni-1.1Zr-1.8Ti).

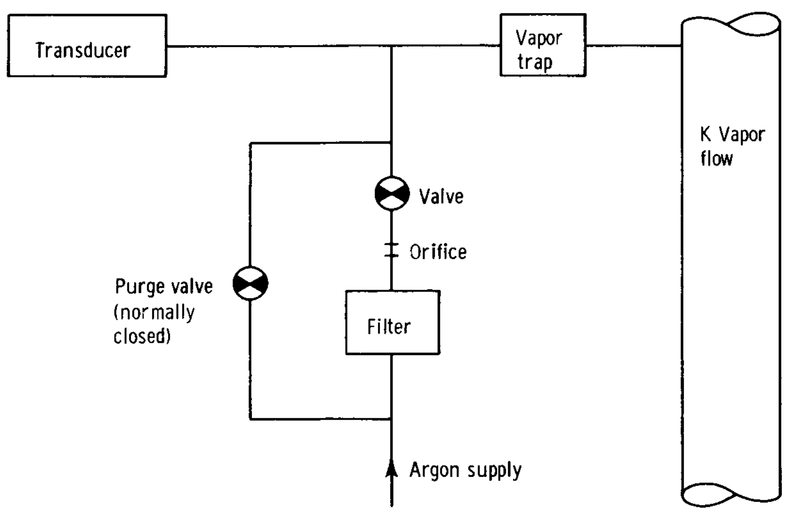



Figure 14. - Efflux pressure-measuring method.

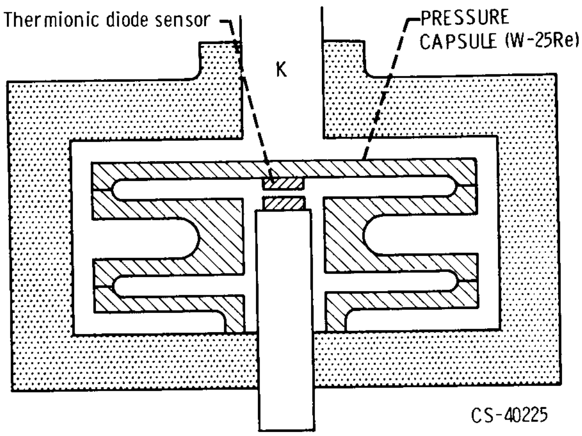



Figure 15. - 1800° F vacuum diode pressure transducer.